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Research Article

Semiempirical Efficiency Calibration in Semiconductor HPGe Gamma-Ray Spectroscopy

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One of the main problems in quantitative gamma-ray spectroscopy is the determination of detection efficiency, for different energies, source-detector geometries, and composition of samples or sources. There are, in principle, three approaches to this issue: experimental, numerical, and semiempirical. Semiempirical approach is based on the calculation of the efficiency for the measured sample on the basis of an experimental efficiency measured on the same detector, but with a calibration source that can be of different size, geometry, density, or composition—the so-called efficiency transfer. The aim of this paper is to analyze the semiempirical approach, using EFFTRAN and MEFFTRAN software as a typical example. These software were used in the Department of Radiation and Environmental Protection, Vinča Institute of Nuclear Sciences, on three HPGe detectors. The results were compared to the experimentally obtained efficiency, and further validation is performed by measuring reference materials issued within the framework of several interlaboratory intercomparisons. The analysis of the results showed that the efficiency transfer produces good results with the discrepancies within the limits of the measurement uncertainty. Also, for intercomparison measurement, u_{test} criterion for the trueness of the result was applied showing that the majority of the obtained results were acceptable. Some difficulties were identified, and the ways to overcome them were discussed.

1. Introduction

Gamma spectrometry is a widely used method for the measurement of gamma-ray emitting radionuclide content in various materials. It is a method of choice for the measurement of environmental samples conducted, for example, during radiological monitoring of the environment and contamination control. This method is based on the interaction of gamma rays emitted from the source and the active volume of the detector. Semiconductor detectors and among them, high-purity germanium (HPGe) detectors, are proven to be very sensitive and have good energy and time resolution. That is why this type of detector is commonly used for gamma-spectroscopic measurements.

In the absence of background, the result of any gamma-spectroscopic measurement is represented by the spectrum of photons originating from the source that are collected by the multichannel analyzer (MCA) with the number of detected photons in a peak at a specific energy being proportional to the activity of the given radionuclide. One of the main problems in quantitative gamma-ray spectroscopy is the determination of detection efficiency, for different energies, different source-detector geometries, and different compositions of voluminous samples or sources. This task represents the efficiency calibration of the detector.

The quality of the results of gamma-spectrometric measurements is dependent on the knowledge of detector efficiency for different sample geometries, chemical compositions, and sample-detector geometries. In reality, measurement depends on the geometry, structure, and the chemical composition of the sample, and the efficiency calibration for each specific case is not always available. That is why several methods for efficiency calibration were developed. There are, in principle, three approaches to this

issue: experimental, numerical, and semiempirical. These methods vary in difficulty, reliability of the obtained results, time and resources required, and so on.

Experimental approach utilizes standardized sources (calibration sources) with composition, density, and geometry that are as close as possible to the measured samples. The direct measurement of different calibration sources containing γ-ray emitters within the energy range of interest, and their subsequent fitting to a parametric function, yields the best results. However, this approach requires a large number of calibration sources, implying a high financial cost, a long counting time, and complicated and time-consuming preparation of the calibration sources. This problem is especially pronounced when environmental samples are of interest due to their diversity in composition and structure [1].

Numerical methods of the efficiency calibration consist of a computer simulation of the processes that contribute to the detection of the emitted photons. Monte Carlo simulation, such as GEANT4, MCNP, EGS, and PENELOPE, can be adapted to the computation of the efficiency of gamma-ray spectrometry detectors [2]. Dedicated codes, such as GESPECOR, LABSOCS, ANGLE, and so on, are specifically tailored to solve most of the problems concerning gamma-spectrometric measurements [3]. Monte Carlo simulation codes are developed to simulate the response of complex particle detectors and for variety of different high energy and nuclear interactions [4]. In case of gamma spectrometry, these codes need defining appropriate processes for interaction of gamma photons with the detector and the corresponding database used in the development of the application for the particular detector, which may be time-consuming and may require proficiency in programming language [5]. Once an application is developed, the use is relatively easy and the results are straightforward. Besides these software packages that simulate detector response to gamma rays, there is also numerical method ("direct matrices multiplication" (DMM) method) based only on general decay scheme developed to determine peak efficiencies as well as the activity of the source [6, 7].

The third approach to the efficiency calibration is the semiempirical approach. It is based on the calculation of the efficiency for the measured sample on the basis of an experimental efficiency curve obtained for the same detector, but with a calibration source that can be of different sizes, geometries, densities, or compositions—the so-called efficiency transfer. The procedure saves time and resources, since sample-specific experimental calibration is avoided. It has been proven especially useful in environmental measurements [8], where an ultimate precision in calibration is usually not required and a variety of different sources might be measured. Many software packages were developed in order to perform efficiency transfer calculations with a known set of parameters. Some are EFFTRAN, MEFFTRAN, ETNA, ANGLE, and so on. The result of the calculation is transfer coefficient, which is the ratio of the efficiency for unknown sample and reference efficiency.

The aim of this paper is to analyze the semiempirical approach to the efficiency calibration of the HPGe detector. A specific example of the efficiency transfer software will be analyzed in more detail, with practical instruction, and advantages and drawbacks pointed out. The results of the testing of this method will also be presented.

1.1. Semiempirical Efficiency Calibration: EFFTRAN and MEFFTRAN. Semiempirical methods for detector efficiency calculation are based on the assumption that the detector efficiency for the measured sample can be calculated knowing the reference efficiency obtained by measuring the calibration source with known composition and activity. This is referred to as "efficiency transfer." The relation between reference efficiency and efficiency for the measured sample is defined in (1), according to the model proposed by Moens et al. [9]:

$$\varepsilon_x = \varepsilon_{\text{ref}} \frac{\overline{\Omega}_x}{\overline{\Omega}_{\text{ref}}}, \tag{1}$$

where ε_x represents the unknown efficiency, ε_{ref} is the reference efficiency, $\overline{\Omega}_x$ is the effective solid angle for the given measurement configuration, and $\overline{\Omega}_{\text{ref}}$ is the effective solid angle for reference configuration. The effective solid angle depends on the geometry of the detector, the source–detector position, and needs to be calculated. Both ε_x and ε_{ref} depend on the gamma photon energy and, through the interaction probabilities, on the chemical composition of the crystal and source.

In order to calculate these effective solid angles, some sort of software is needed for solving the partial differential equations. Often in the calculation, Monte Carlo integration is used as a suitable choice for many-dimensional systems. This calculation requires relatively precise information on geometry of the detector (crystal geometry, housing geometry and composition, active and inactive layers, etc). Also, the information on both calibration source and measured sample has to be provided (diameter, filling height, matrix composition, thickness of the container, etc.). Because the model of the sample, as well as the detector crystal, can be constructed from cylinders only, the only complex operation required in the code is the calculation of the path length traversed through the cylinders defining the counting geometry by a gamma-ray originating at an arbitrary location [10].

The procedure for obtaining the unknown efficiency is as follows. Firstly, a calibration source with known composition and activity is measured, and the detection efficiency ε_{ref} has to be calculated for all energies emitted from the source using the following equation:

$$\varepsilon_{\text{ref}} = \frac{N \cdot C(E)}{t \cdot P_\gamma \cdot A}, \tag{2}$$

where N is the number of detected gamma photons, $C(E)$ is the coincidence summing correction factor, t is the measurement time, P_γ is the emission probability at given energy E, and A is the activity of the radionuclide present in the calibration source.

As with all measurement, also in this case, a measurement uncertainty $u(\varepsilon_{\text{ref}})$ has to be defined. It is expressed as a combined standard uncertainty using the following equation:

$$u_{\text{ref}}(\varepsilon) = \sqrt{(\delta A)^2 + (\delta N)^2 + (\delta M)^2 + (\delta C)^2}, \quad (3)$$

where δA is the relative uncertainty of the activity of the radionuclide present in the calibration source (1-2%), δN is the relative statistical uncertainty, and δM includes all other contributions to the uncertainty such as measurement of the reference material mass, the uncertainty of the positioning of the sample on the detector, measurement time uncertainty, and radioactive decay during measurement, and so on, which are estimated to be 2%. Finally, δC is the uncertainty of the coincidence correction factor (≈1.2%).

Then, the geometrical characteristics of the detector need to be defined. Due to the specific shape of the detector crystal and surrounding material, the geometry of the detector can be defined as a set of cylinders with a certain radius and height, made of known material. These data are usually available from the manufacturer of the detector itself. Furthermore, the reference source and measured sample characteristics are defined, also as a set of cylinders. The material of both calibration source and sample is defined using its chemical formulae, the percent of each compound in the total mass of the source or sample, and the density of the matrix. After all these data are entered, the calculation gives the transfer coefficients which, when multiplied with the reference efficiency obtained by measuring the calibration source, yield the unknown efficiency for the measured sample.

As a typical example of efficiency transfer software, here we will use EFFTRAN and MEFFTRAN software. EFFTRAN, an efficiency transfer software, is dedicated to calculation of efficiency transfer for cylindrical samples, while MEFFTRAN performs the same calculations for the Marinelli beaker [10, 11]. The software is organized as a Microsoft excel file with three modules. There is a module for defining the material of the calibration source and measured sample (Material), a module for calculation of the efficiency transfer (Efficiency Transfer), and a module for calculation of coincidence correction factors (Coincidence Correction). In the module Efficiency Transfer, the geometrical characteristic of the detector crystal has to be defined. This means that also, the material of the crystal and detector window should be defined, as well as the thickness of the dead layers and window to crystal gap.

All the data that are required are not always known and cannot be precisely defined, thus contributing to the measurement uncertainty. However, the lack of precision and uncertainties rising from poor knowledge of the composition of the sample cannot be avoided.

The combined relative uncertainty of the efficiency ε_x obtained by MEFFTRAN or EFFTRAN can estimated according to the following expression:

$$u(\varepsilon_x) = \sqrt{\left(u\left(\varepsilon_{\text{ref}}\right)\right)^2 + \left(u(C)\right)^2 + \left(u_{\text{D}}\right)^2 + \left(u_{\text{S}}\right)^2}, \quad (4)$$

where $u(\varepsilon_{\text{ref}})$ is the relative uncertainty of the reference efficiency value, defined in (2), $u(C)$ is the uncertainty of the transfer factors calculated by the program as a statistical uncertainty of the Monte Carlo integration (≈1.2%), u_{D} is the uncertainty associated with the geometry of the detector, and u_{S} is the uncertainty associated with the characteristics of the sample. As it can be seen from (4), the parameters contributing to the uncertainty are combined as independent variables.

The uncertainty of the parameters of the detector geometry u_{D} can be estimated by varying each parameter and calculating the amount of change it produces on the transfer factors. In this way, the uncertainty can be estimated to be around 1% for crystal diameter and length, and crystal cavity diameter and length. According to this estimation, the contribution u_{D} can be obtained by combining these uncertainties as a square root of sum of squares [5].

The characteristics of the calibration source and measured samples also contribute to the measurement uncertainty via parameter u_{S}.

In the case of EFFTRAN, the density of the samples was calculated by dividing the measured mass of the sample with the volume of the sample. Therefore, the contribution of the density to the uncertainty parameters is the combined uncertainty of mass and volume (1-2%). The chemical composition of the container can be well defined, but for the sample, the situation is more complicated, and poor knowledge of the chemical composition can be the source of larger uncertainty.

The definition of the chemical composition of the material can significantly contribute to the uncertainty budget. In order to define this contribution, an in-depth analysis has to be performed. This will be the subject of the investigation that is under way. One simple way to estimate this contribution is to vary the composition of the sample by adding or omitting some elements or compounds. Of course, this does not apply to the samples with known composition such as water and charcoal. In case of soil and grass, we have varied the composition in order to see how these changes reflect on the result of the efficiency transfer. It has been determined that omitting Fe from the composition of the soil leads to changes in the result that are around 2% for both EFFTRAN and MEFFTRAN, while changing the content of C leads to the changes in the results that span from 1% in case of EFFTRAN to 8% in case of MEFFTRAN. Much larger changes are observed in case of grass composition, namely, the change of C content with respect to the cellulose content. These changes ranged from 7 to 29%, with the largest influence noticed for the lowest energy. It is noticed that the influence of the composition lowers with the rising energy. Also, in some cases, such as grass, the influence of the chemical composition can be larger than the influence of the sample thickness. How these changes combine with each other (can one simply sum or multiply all changes) is yet to be analyzed. For the sake of simplicity in this paper, the contribution to the uncertainty arising from the chemical composition definition is estimated to be 10% average, for all energies.

In the case of MEFFTRAN, since all samples were Marinelli beakers, the only variable parameters of the sample geometry are sample filling height and mass. The contribution of 0.8%

Table 1: The uncertainty budget.

	Uncertainty (%)	
	EFFTRAN	MEFFTRAN
u_D		
Crystal diameter and length	1	1
Crystal cavity diameter and length	1	1
Total u_D	**1.41**	**1.41**
u_S		
Matrix density	1-2	1.64
Chemical composition	1–10	2–10
Total u_S	**10–10.2**	**10.1**
$u(\varepsilon_{ref})$		
Activity (A)	1-2	
Count (N)	<1	
Positioning, time, mass, and so on	2	
Coincidence correction factor (C)	1.2	
Total $u(\varepsilon_{ref})$	**3**	**3**
Total $u(\varepsilon_x)$	**~10.5**	

for the sample filling height was included in the uncertainty budget. This contribution was calculated by conducting the efficiency transfer for 5 different filling heights (105 mm, 100 mm, 95 mm, 90 mm, and 85 mm) and calculating the ratio between the different transfer coefficients. It is then established that the 1% change in height leads to 0.8% change in transfer coefficients, thus contributing to the u_S with 0.8%. The uncertainty of the sample mass is estimated to be 1%. Since the software requires the density of the matrix to be defined, these two were combined to produce the square of the sample density uncertainty equal to 1.64%. The contributions u_D and $u(C)$ are the same as in the case of EFFTRAN.

The uncertainty budget is presented in Table 1.

After all the calculations are done and the efficiency for the measured sample is obtained, it is crucial to perform some sort of validation of the results. This can be done by comparing the calculated efficiency with the experimental one, obtained by measuring a reference sample with the known activity. Of course, this reference sample has to be different from the one used in the calculation as a calibration source. This can be achieved also by taking part in the interlaboratory intercomparisons, where the results obtained using a calculated efficiency are compared to the target value provided by the organizer and the accuracy and the precision of the result is assessed.

2. Results and Discussion

The semiempirical calculation of the detection efficiency is readily performed in the Department of Radiation and Environmental Protection, Vinča Institute of Nuclear Sciences, on three HPGe detectors (two p-type detectors named "Detector 1" and "Detector 3" and one n-type detector named "Detector 2"). For this purpose, EFFTRAN and MEFFTRAN software are used. As a reference source for EFFTRAN, point sources (^{241}Am, ^{109}Cd, ^{137}Cs, ^{54}Mn, and ^{60}Co (LMRI Coffret d'etalons), type gamma ECGS-2, uncertainty about 1%) are used, and for MEFFTRAN, a certified radioactive standard purchased from Czech Meteorological Institute (Marinelli beaker filled with silica resin) is used. The radionuclides present in this standard are ^{214}Am, ^{109}Cd, ^{137}Cs, ^{54}Mn, ^{113}Sn, ^{203}Hg, ^{88}Y, ^{139}Ce, ^{113}Sn, ^{57}Co, and ^{60}Co, with the energies that span from 60 keV to 1836 keV and with the uncertainties from 1.1 to 1.9%. The set of radioactive standards used to validate the accuracy of the transferred efficiency were produced in our laboratory, using certified standard solution 9031-OL-427/12, ERX Prod no. 170712-1374036 and 9031-OL-426/12, ERX Prod no. 170712-1374034. The standard solution used for production of reference materials contained ^{214}Am, ^{109}Cd, ^{137}Cs, ^{54}Mn, ^{113}Sn, ^{203}Hg, ^{88}Y, ^{139}Ce, ^{113}Sn, ^{57}Co, and ^{60}Co, with the energies that span from 60 keV to 1836 keV and with the uncertainties from 0.5 to 1.7%. In Table 2, these reference materials are listed along with their measurement geometries, chemical composition, and packing density, which are all basically the data necessary for the calculation. For EFFTRAN, a total of 11 reference materials were used, while one was used for checking the accuracy of the calculation in MEFFTRAN.

Table 2: List of reference materials prepared in the laboratory and used for comparison between the calculated and experimental efficiency.

Matrix material	Chemical composition	Density (g/cm^3)	Measurement geometry
Charcoal	C (100%)	0.486	Cylinder, volume 100 ml
		0.454	Cylinder, volume 200 ml
Soil	SiO_2 (90.00%) K (4.00%) Fe (1%) C (4.00%) Others (1%)	1.381	Cylinder, volume 100 ml
		1.426	Cylinder, volume 200 ml
Sand	SiO_2 (100%)	1.591	Cylinder, volume 100 ml
		1.556	Cylinder, volume 200 ml
		1.9	Marinelli beaker, volume 0.5 l
Mineralized grass	C (99%) Others (1%)	0.300	Cylinder, volume 100 ml
		0.256	Cylinder, volume 100 ml
Water	H_2O (100%)	1.012	Cylinder, volume 125 ml
		1.011	Cylinder, volume 250 ml
Aerosol	SO_4 (15%) NH_4 (15%) NO_3 (15%) CH (50%) Others (5%)	0.572	Vial, volume 50 ml

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Since the reference material used for validation of the results contained different radionuclides than point sources, the efficiency calculated from the measurement of point sources was used to obtain a calibration curve. This was achieved by fitting the experimental efficiencies with a function given in (5). This calibration curve was used to calculate the efficiencies for the energies that are emitted by the radionuclides contained in the reference samples:

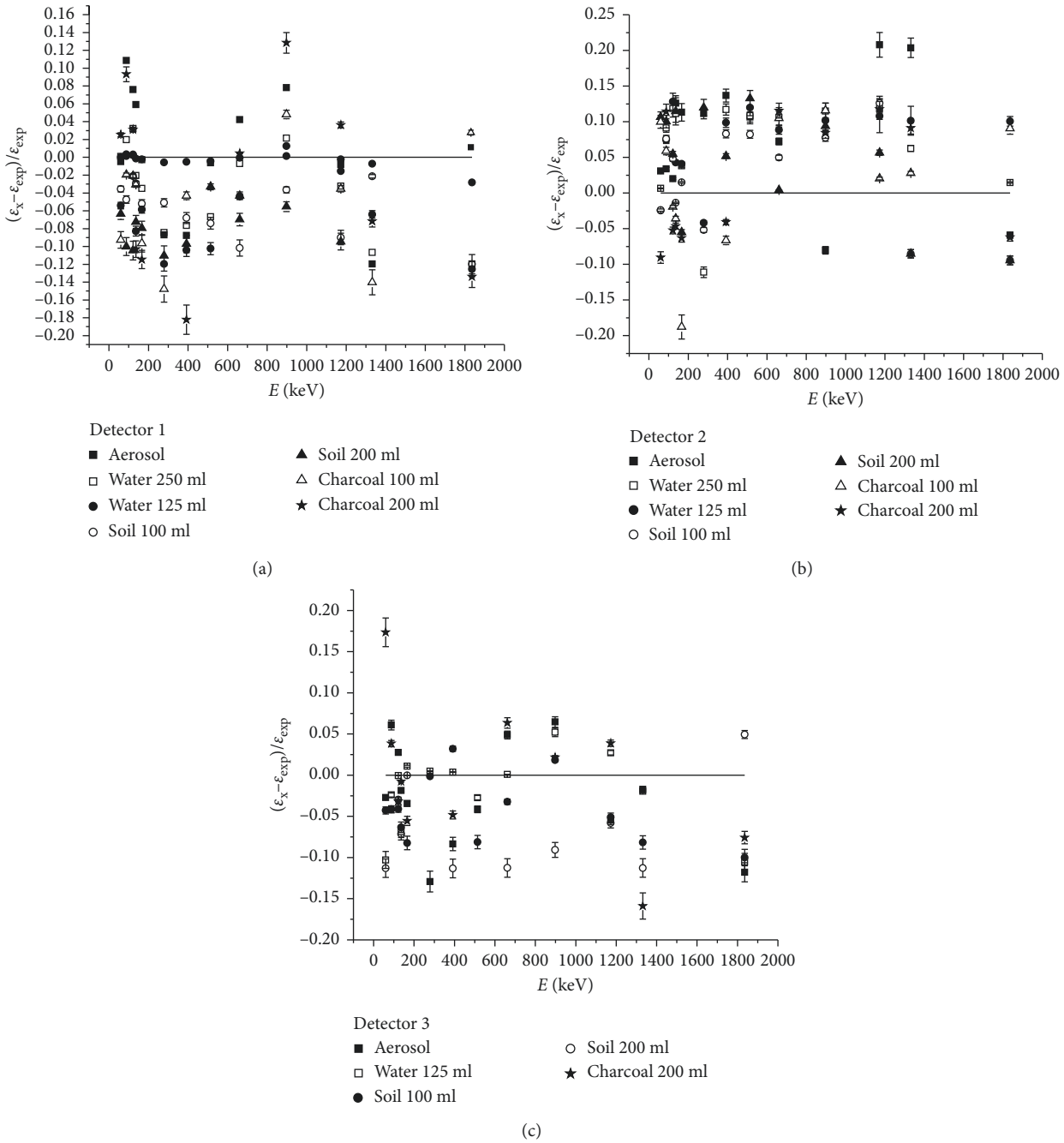

Figure 1: The relative discrepancy $(\varepsilon_{\text{EFFTRAN}} - \varepsilon_{\text{exp}})/\varepsilon_{\text{exp}}$ for all three detectors (a–c) and the investigated reference materials.

$$\ln \varepsilon_{\text{ref}} = \sum_{i=1}^{5} a_i (\ln E)^{i-1}, \tag{5}$$

where ε_{ref} is the reference efficiency, E is the energy, and a_i are the coefficients of the fit.

The discrepancy between the calculated efficiency, $\varepsilon_{\text{EFFTRAN}}$, and the experimental efficiency, ε_{exp}, in case of EFFTRAN is presented in Figure 1, for all three detectors for aerosol, water in the cylinder of 125 ml and 250 ml, charcoal in the cylinder of 100 ml and 200 ml, and soil in the cylinder of 100 ml and 200 ml.

The measurement uncertainty of the results is calculated according to (4).

As it can be seen from Figure 1, relative differences of the efficiency for different matrices placed in different geometries for all three detectors are mainly in the range of ±10% (due to the geometry of the housing and end cap of Detector 3, some geometries were not investigated). As it can be seen, EFFTRAN produces results that are relatively in good accordance with the experimental ones. Majority results are within a 10% margin that falls within the uncertainty limits. This is the case for well defined, low absorbing matrix with simple chemical composition; hence, the accordance

between results is expected. It is however noticeable that EFFTRAN produces higher results for Detector 2, which is an n-type detector with Be window. For soil matrix, EFFTRAN produces results that differ from the experimental ones in the mid-energy region for all detectors. The efficiency is mainly underestimated for the p-type and overestimated for the n-type detector. Since the systematic influence of the matrix composition and the density are the largest at low energies and falls off with increasing energy, some discrepancies can be attributed to a lack of point sources that cover some regions of spectrum. Thus, the starting point for EFFTRAN calculation is somewhat incomplete, which can be resolved by measuring more point sources that produce energies in the desired region (e.g., ^{85}Sr and ^{113}Sn, or ^{152}Eu), which are unavailable at present.

Also, since the calculation was performed using point-source efficiency as a starting point, the discrepancies that are of the order of magnitude of the measurement uncertainty are quite acceptable and larger discrepancies should be expected. This can serve as an indication of the limitations of this approach. Using point sources or some other sources that differ significantly from the measurement geometry is not recommendable, better results are achieved using some more similar geometries for the reference efficiency. In that case, the calculations conducted in the laboratory produced results that differ from the experimental ones for 2-3%. [5].

In case of MEFFTRAN, due to its dimensions, Detector 3 was not used for measurements. In the case of Marinelli Sand for Detectors 1 and 2, the discrepancy of the calculated values from the measured values is in the range of −3.9% to +1.5%. These discrepancies are within the limits of measurement uncertainty. The largest discrepancies are noticed for the lowest energy (59 keV), which leads to the conclusion that the reference calibration should be done using calibration standard that contains ^{210}Pb. In that case, the lowest energies in the spectrum would be covered with two points in the reference calibration curve, leading perhaps to a better definition of the curve slope [12].

In order to further check the accuracy of the efficiency transfer, several reference materials issued within the framework of different interlaboratory intercomparisons were measured. The activities were then calculated using the efficiency obtained by EFFTRAN and MEFFTRAN and compared with the reference values provided by the organizer (IAEA). The measured materials were as follows:

(i) Hay sample (IAEA-TEL-2012-03)

(ii) Soil sample (IAEA-TEL-2013-03)

(iii) Seaweed, water, and sediment samples (IAEA-TEL-2014-03)

(iv) Sediment sample 662-1 from the South Transdanubian Inspectorate for Environmental Protection Nature Conservation and Water Management, Hungary.

Not all samples were possible to measure on all detectors, but at least one measurement of each sample was conducted.

The accuracy of the results is tested using u_{test} criterion recommended by the IAEA and defined in the following (5) [13]:

$$u_{\text{test}} = \frac{\left|A_{\text{IAEA}} - A_{\text{LAB}}\right|}{\sqrt{u_{\text{IAEA}}^2 + u_{\text{LAB}}^2}}, \tag{6}$$

where A_{IAEA} represents the target value of the activity, A_{LAB} is the activity reported by the participating laboratory, u_{IAEA} is the uncertainty of the target value, and u_{LAB} is the uncertainty of the result reported by the participating laboratory.

According to this criterion, the results are graded as acceptable (A) in case of $u_{\text{test}} \leq 2.5$ and not acceptable (N) in case of $u_{\text{test}} > 2.5.8$.

In Tables 3 and 4, the measurement results of the mentioned reference materials are listed with measurement uncertainty of 1σ level, along with the target value and the u_{test} result. In these tables, the letter N is added to the result which is not acceptable. Also, the target values denoted with the asterisk are obtained as a robust mean value of the results reported by all the participant laboratories with the standard deviation instead of the measurement uncertainty.

In case of EFFTRAN, two results were unacceptable. Since there were 13 radionuclides in total for which the activity was calculated, this stands for good agreement, especially when we notice that the result for the same radionuclide (^{137}Cs) was acceptable in other reference materials.

As it can be seen from Table 4, all but one result are acceptable, proving that semiempirical calculation of the efficiency produces accurate efficiencies for all investigated sources.

Discrepancies between efficiency calibration by EFFTRAN and MEFFTRAN software and experimentally obtained detection efficiencies are mainly due to insufficiently known detector geometry parameters and matrix composition for measured samples and reference materials. In order to achieve the best possible concurrence with experimentally obtained values, the optimization of these parameters was performed. Nevertheless, some of the parameter values like dead layer thickness, bulletization of the germanium crystal, and chemical composition and inhomogeneity of matrix materials could not be ideally optimized and still need improvement. Also, in cases presented in Figure 1, the efficiency transfer was performed based on point-source efficiency calibration. Considering that the initial and transferred efficiency relates to very different geometries and matrices, certain deviations are inevitable. But still, the majority of the results are in agreement within about 10% uncertainties, which are satisfying for environmental sample measurements.

This also shows that semiempirical calibration is not overly sensitive to small variations in sample filling height and mass, while good definition of the matrix chemical composition contributes to the reliability of the results. The good definition of the chemical composition of the material is shown to have the most pronounced influence on the results especially for low energies. Also, it can be recommended that the efficiency transfer should be performed using the most

Table 3: The measured activity concentrations of radionuclides obtained with efficiency calculated by EFFTRAN, along with the target values, and evaluation of accuracy using u_{test} parameter.

	A_{LAB} (Bq/kg)		Target value	u_{test}	
	n-Type detector 2	p-Type detectors 1 and 3	(Bq/kg)	n-Type detector 2	p-Type detectors 1 and 3
IAEA-TEL-2014-03 sediment sample					
^{238}U	18 ± 1	21 ± 4	16.0 ± 3.8*	0.51	0.91
^{226}Ra	20.8 ± 0.8	22 ± 1	19.0 ± 4.8*	0.37	0.61
^{137}Cs	14.3 ± 0.5	14.3 ± 0.5	12.0 ± 0.4	**3.59N**	**3.59N**
^{228}Ac	12.5 ± 0.4	12.9 ± 0.7	12.1 ± 1.5*	0.26	0.48
^{40}K	292 ± 9	292 ± 9	270 ± 27*	0.77	0.77
Sediment sample 662-1					
^{137}Cs	18 ± 3	16.9 ± 0.8	14.0 ± 0.8	1.29	2.56
^{228}Ac	38.7 ± 3.1	35 ± 2	37 ± 3	0.39	0.55
^{40}K	555 ± 61	552 ± 20	470 ± 40	1.16	1.83
IAEA-TEL-2012-03 hay sample					
^{137}Cs	760 ± 20	820 ± 30	785 ± 24	0.80	0.91
^{134}Cs	270 ± 20	320 ± 30	306 ± 20	1.27	0.39
IAEA-TEL-2014-03 water					
^{137}Cs	—	12.6 ± 0.4	12.06 ± 0.1	—	1.31
^{134}Cs	—	21.3 ± 0.7	21.4 ± 0.2	—	0.14
^{210}Pb	—	38 ± 5	49.87 ± 1.23	—	2.31

*Robust mean.

Table 4: The measured activity concentrations of radionuclides obtained with efficiency calculated by MEFFTRAN, along with the target values, and evaluation of accuracy using u_{test} parameter.

	A_{LAB} (Bq/kg)		Target value	u_{test}	
	p-Type detector 1	n-Type detector 2	(Bq/kg)	p-Type detector 1	n-Type detector 2
Sediment sample IAEA-Tel-2014					
^{210}Pb	—	23 ± 2	19.6 ± 4.5*	—	0.67
^{238}U	23 ± 3	19 ± 2	16 ± 3.8*	1.35	0.59
^{226}Ra	18 ± 1	17.4 ± 1.2	19 ± 4.8*	0.29	0.32
^{137}Cs	12.4 ± 0.7	12.4 ± 0.7	12.0 ± 0.4	0.50	0.50
^{228}Ac	10.9 ± 0.7	11.6 ± 0.8	12.1 ± 1.5*	0.72	0.29
^{40}K	280 ± 20	280 ± 20	270 ± 27*	0.30	0.30
^{212}Pb	9.3 ± 0.6	11 ± 1	12.2 ± 1.5*	1.79	0.67
^{212}Bi	13 ± 1	13 ± 1	12.2 ± 1.2*	0.53	0.62
Seaweed sample IAEA-Tel-2014					
^{137}Cs	21 ± 1	20 ± 1	22.96 ± 0.45	1.79	1.93
^{134}Cs	8.0 ± 0.7	8.0 ± 0.7	8.27 ± 0.2	0.37	0.40
^{228}Ac	2.8 ± 0.4	2.8 ± 0.4	2.5 ± 0.7*	0.37	0.41
^{40}K	1580 ± 70	1580 ± 70	1780 ± 150*	1.21	1.17
^{212}Pb	2.0 ± 0.1	2.0 ± 0.1	2.6 ± 0.6*	0.99	0.94
^{226}Ra	5.7 ± 0.5	—	5.1 ± 3.7*	0.16	—
Hay sample IAEA-TEL-2012					
^{137}Cs	750 ± 40	740 ± 40	785 ± 24	0.64	0.99
^{134}Cs	280 ± 20	300 ± 20	306 ± 20	0.95	0.35
Soil sample IAEA-Tel-2013					
^{210}Pb	480 ± 30	690 ± 40	595 ± 19	**3.24N**	2.15
^{241}Am	—	1.6 ± 0.2	1.8 ± 0.1	—	0.81
^{238}U	—	23 ± 3	23.6 ± 0.7	—	0.19
^{40}K	190 ± 10	190 ± 10	207.7 ± 8.3	1.36	1.36
^{137}Cs	107 ± 6	110 ± 6	118.6 ± 2.9	1.74	1.29
^{208}Tl	10.5 ± 0.8	10.3 ± 0.6	11.5 ± 0.6	1	1.41
^{212}Pb	30 ± 3	27.5 ± 2	31.0 ± 1.2	0.31	1.51
^{228}Ac	30 ± 2	30 ± 2	32.4 ± 1.6	0.94	0.94

*Robust mean.

similar sample geometry and composition as possible; that is, it is better to use almost anything else instead of point source for reference efficiency measurement.

3. Conclusion

One of the main problems in quantitative gamma-ray spectroscopy is the determination of detection efficiency, for different energies, different source-detector geometries, and different compositions of voluminous samples or sources. This task is defined as an efficiency calibration of the detector, and there are several approaches to resolving this problem. Semiempirical approach to efficiency calibration (so-called efficiency transfer) takes advantage of positive attributes of both experimental and numerical approaches, simultaneously minimizing their drawbacks. Application of EFFTRAN or MEFFTRAN software is the most practical for this purpose, giving the values of the transferred efficiencies that agree on a satisfactory level with those obtained experimentally. This approach needs a reference efficiency which should be obtained by measuring the certified calibration source, which is then used for calculation performed by the software. After the unknown efficiency is obtained, it is highly recommended to validate the results. The most practical way to do that is to measure some reference materials with known activity, that is, participate in the interlaboratory intercomparison. Also, an in-depth analysis of uncertainty budget is mandatory in order to assess the contribution of the calculated efficiency to the measurement uncertainty.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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